Special Topics on Basic EECS I
VLSI Devices
Lecture 13

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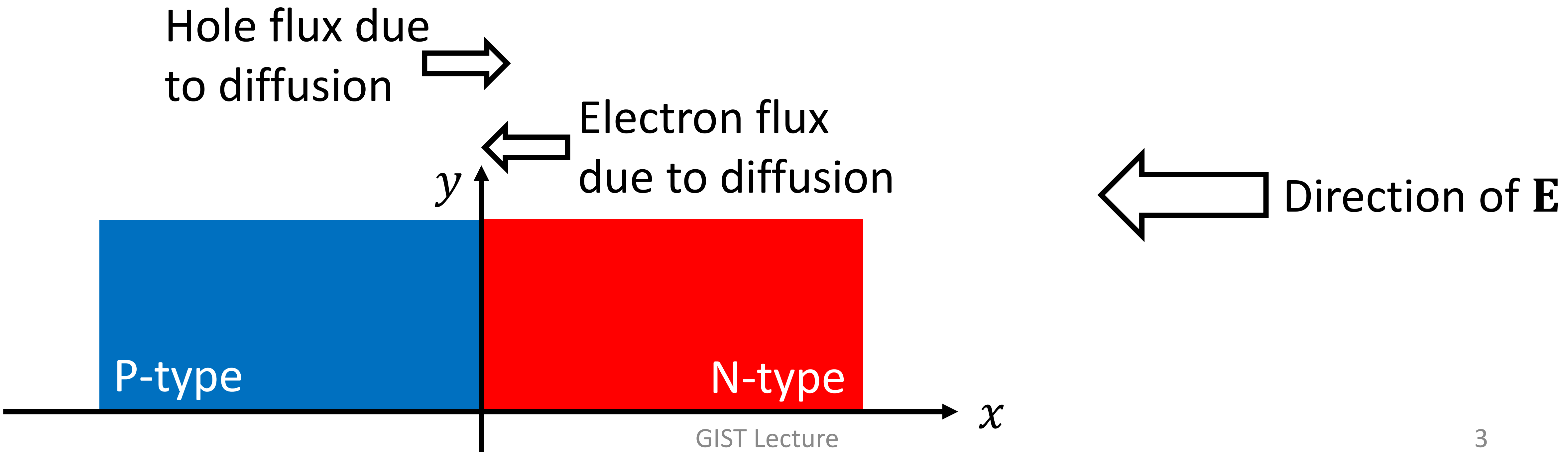
PN junction

- Where can we find PN junctions?

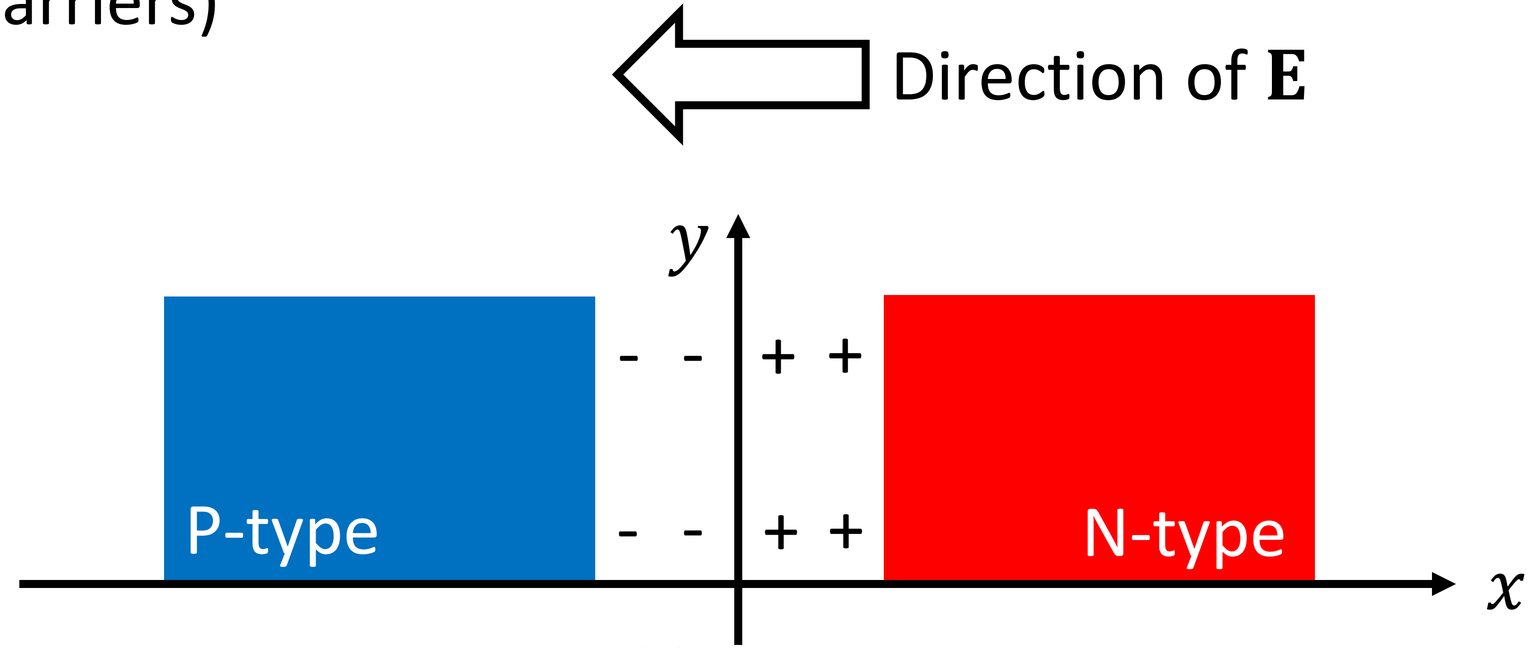
Qualitative description (1)

- Built-in electric field
  - Strong diffusion current density
  - At equilibrium, the net flux must vanish.
  - An electric field is required.



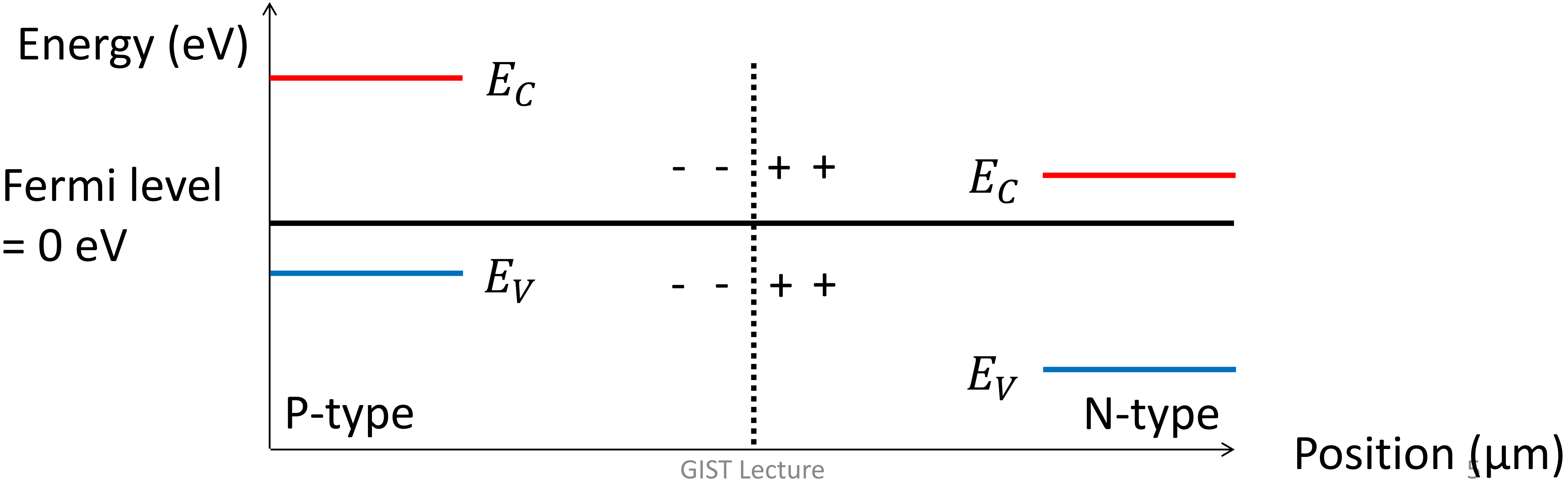
Qualitative description (2)

- How to build an electric field
  - We need the net charge density, ρ.
  - Positive charges in the n-type region, negative p-type
  - These charges can be supplied by the depletion layer. (Eliminating charge carriers)



Energy band diagram at equilibrium

- At thermal equilibrium, the Fermi level must remain flat across the entire pn junction.
  - Away from the junction, the energy bands are flat.
  - Near the junction, a smooth transition of E_C and E_V



Built-in potential

- Assume that N_d is the donor density and N_a is the acceptor density.
  - In the n-type boundary,

$$N_d = n_i \exp \frac{\phi}{k_B T/q}, \qquad \phi = \frac{k_B T}{q} \ln\left(\frac{N_d}{n_i}\right)$$ Taur, Eq. (2.71)

  - In the p-type boundary,

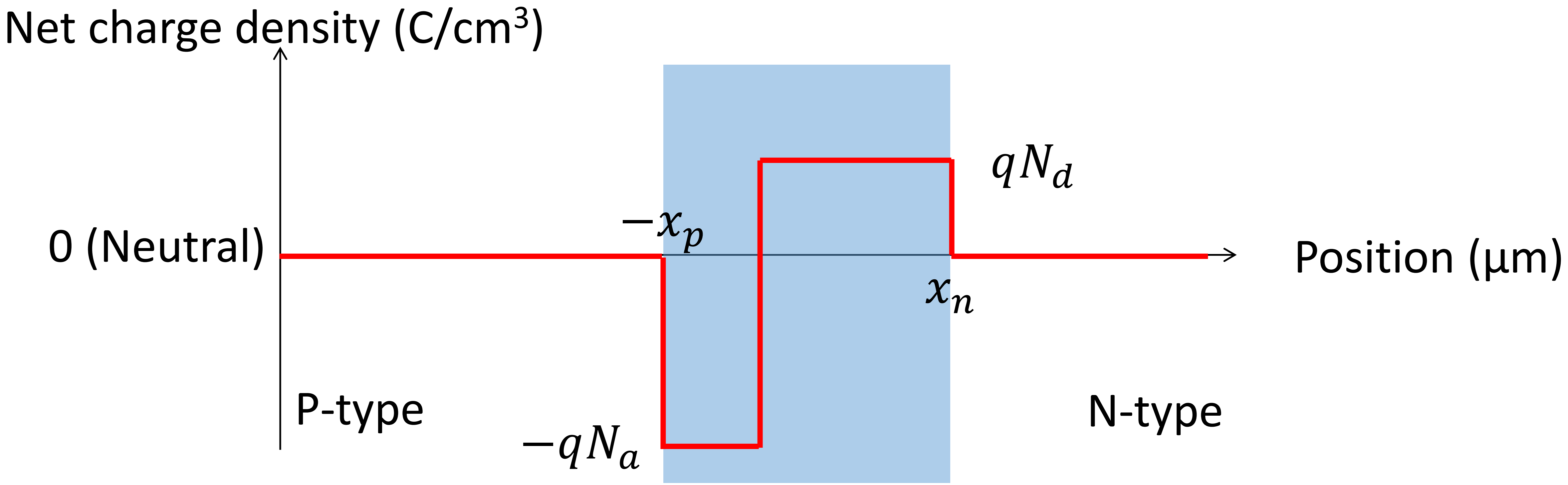
$$N_a = n_i \exp \frac{-\phi}{k_B T/q}, \qquad \phi = -\frac{k_B T}{q} \ln\left(\frac{N_a}{n_i}\right)$$ Taur, Eq. (2.72)

  - Their difference, the built-in potential (ϕ_{bi}) is

$$\phi_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_d N_a}{n_i^2}\right)$$ Taur, Eq. (2.73)

Depletion approximation

- Electron and hole densities are assumed to be negligible in the entire band-bending region.
  - Depletion region(/layer) from $-x_p$ to x_n. $N_a x_p = N_d x_n$



Analytic solution

- The Poisson equation in the depletion region
  - In the p-type region,

$$\frac{d^2\phi}{dx^2} = \frac{q}{\epsilon} N_a$$

Taur, Eq. (2.77)

  - In the n-type region,

$$\frac{d^2\phi}{dx^2} = -\frac{q}{\epsilon} N_d$$

Taur, Eq. (2.76)

  - Assuming vanishing electric fields at $-x_p$ and x_n,

$$\mathcal{E}_m = \left|\frac{d\phi}{dx}\right|_{x=0} = \frac{q}{\epsilon} N_d x_n = \frac{q}{\epsilon} N_a x_p$$

Taur, Eq. (2.78)

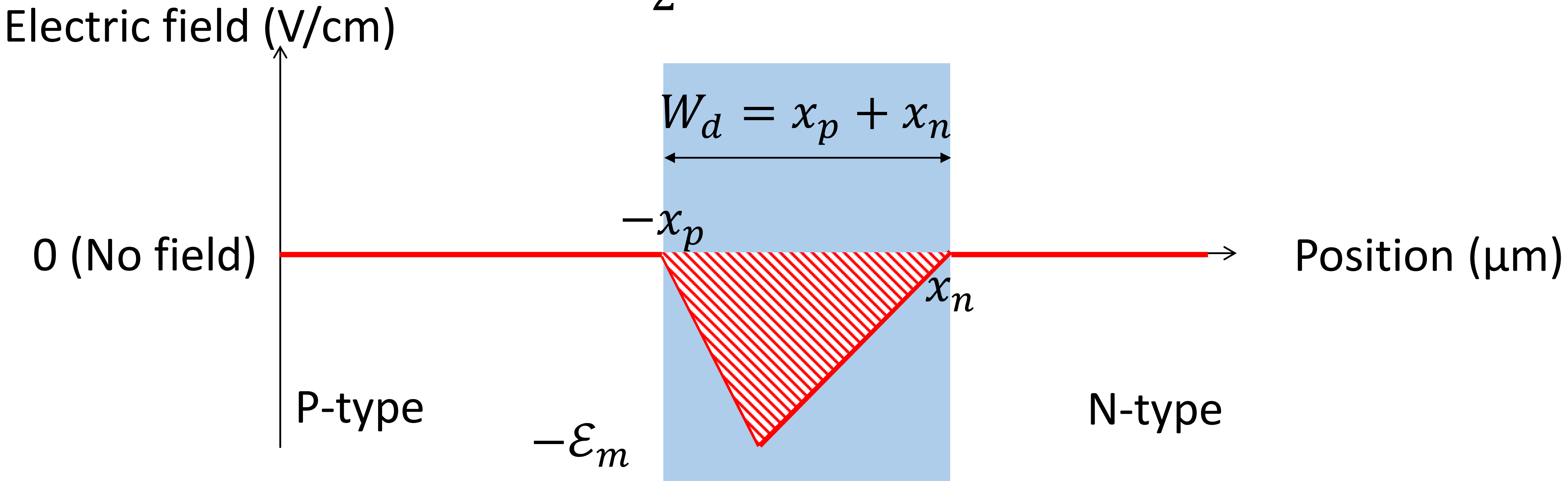
Electric field

- Negative ➔ Pushing carriers back to their majority regions
  - Integrating once again,

$$-\frac{\mathcal{E}_m W_d}{2} = -\phi_{bi}$$

Valid at equilibrium

Taur, Eq. (2.79)



Depletion width

- Calculate the depletion width, W_d.
  - The maximum electric field is

$$\mathcal{E}_m = \frac{q}{\epsilon} W_d \frac{N_a N_d}{N_a + N_d}$$

  - Eliminating $\mathcal{E}_m$,

$$W_d = \sqrt{\frac{2\epsilon(N_a + N_d)\phi_{bi}}{qN_aN_d}}$$

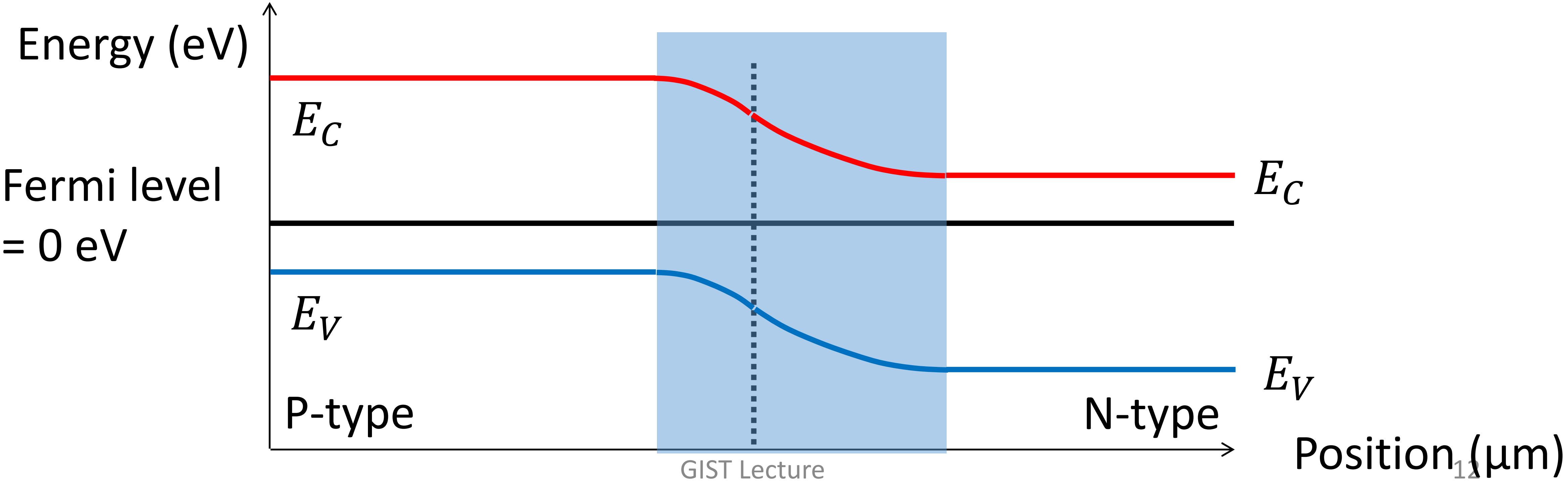
Taur, Eq. (2.80)

Example 4-1 of Hu's book

- Assume that N_d = 10^{20} cm^{-3} and N_a = 10^{17} cm^{-3}.
  - The built-in potential becomes about 1.012 V.
  - The depletion width is about 115 nm.
  - Moreover, $x_p \gg x_n$.

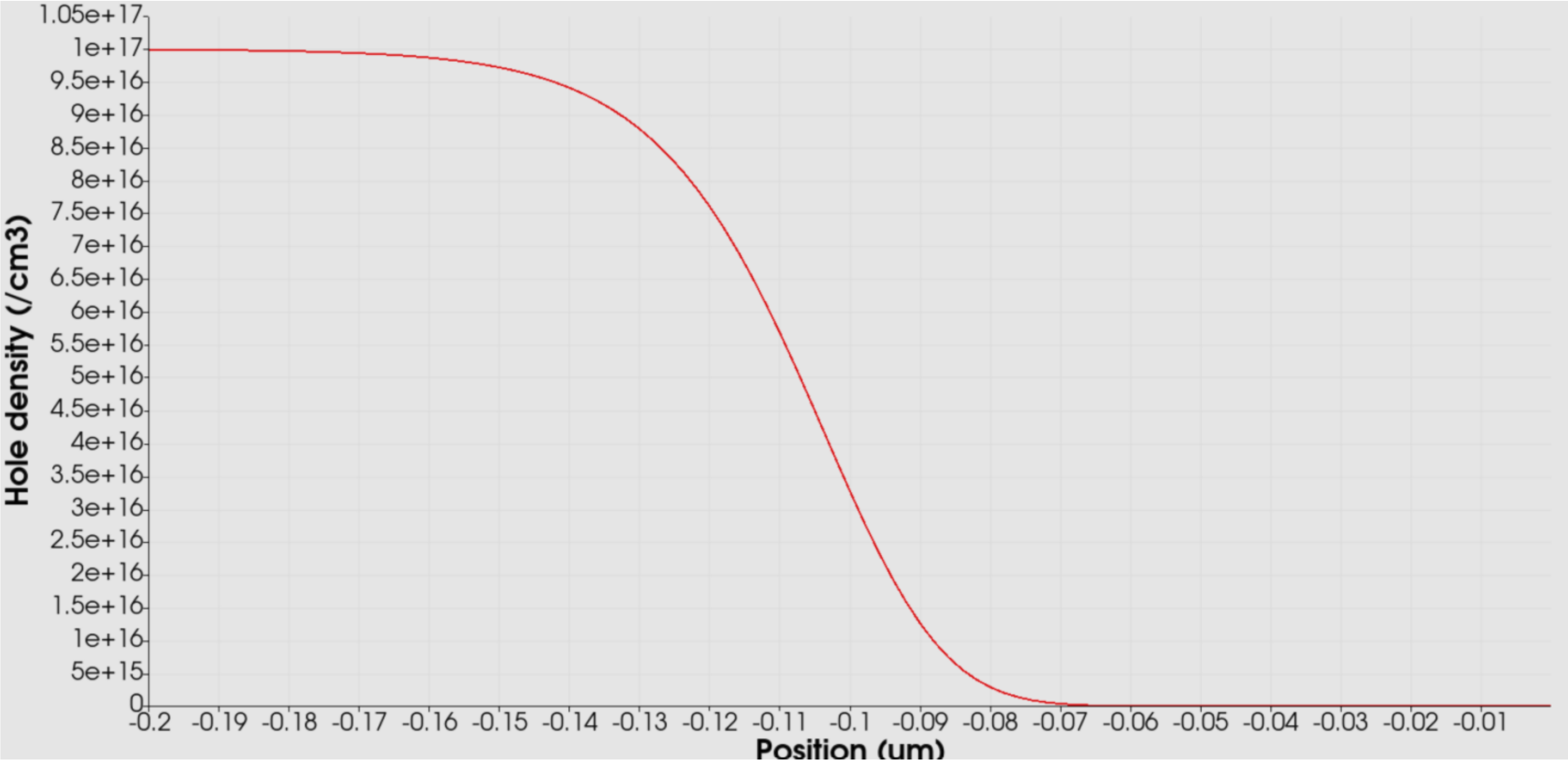
Energy band diagram, again

- Near the junction, a smooth transition of E_C and E_V
  - Parabolic curves
  - Energy barrier seen by each carrier



Revisiting the depletion approximation

- Numerical solution (N_d = 10^{20} cm^{-3} and N_a = 10^{17} cm^{-3})
  - The hole density does not drop abruptly. (Length scale: L_D)



Externally biased junctions

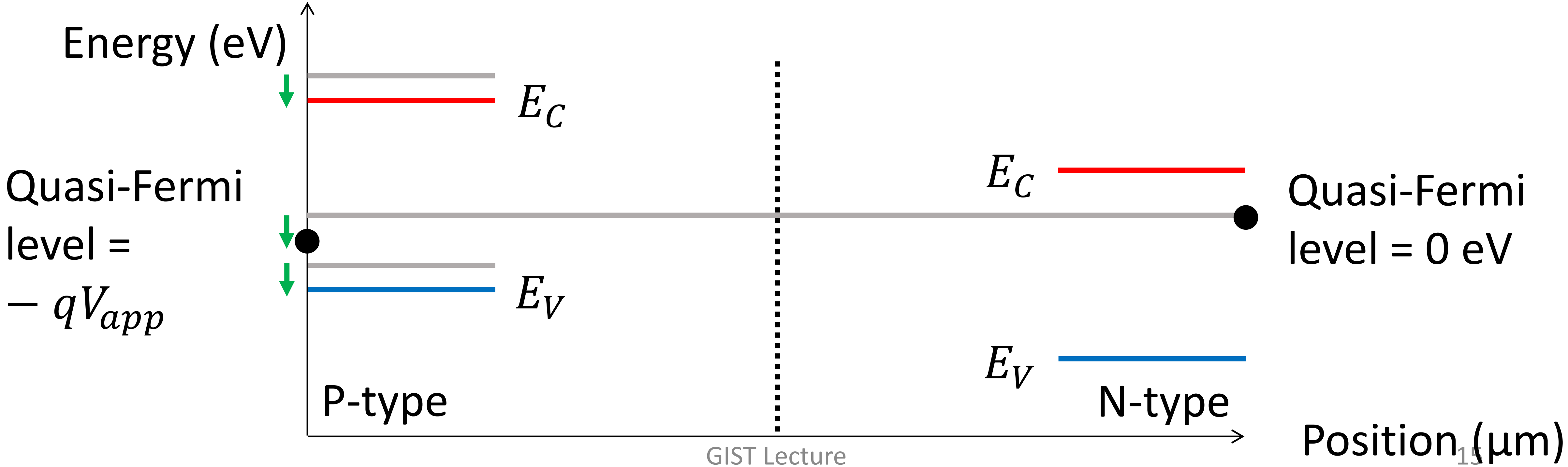
- Consider a positive bias applied to the p-type contact. (Forward-bias)
  - Boundary condition for the electrostatic potential
    $$\phi\left(V = V_{app}\right) = \phi(V = 0) + V_{app}$$
  - Boundary condition for the quasi-Fermi potentials
    $$\phi_n\left(V = V_{app}\right) = V_{app}$$
    $$\phi_p\left(V = V_{app}\right) = V_{app}$$

Energy band diagram

- We cannot define the Fermi level any more.
  - Still, quasi-Fermi potentials are available.
  - The total potential difference is

$$\phi_{bi} - V_{app}$$

Taur, Eq. (2.81)



Thank you!